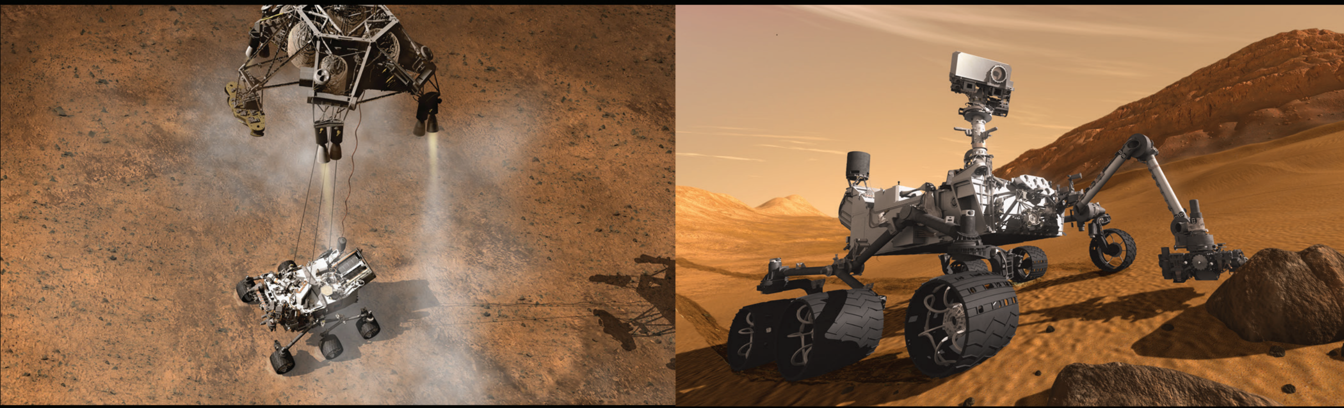
PLANETARY SCIENCE

THE SCIENCE OF PLANETS AROUND STARS

SECOND EDITION



GEORGE H. A. COLE
MICHAEL M. WOOLFSON

CRC Press
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This book is dedicated to the memory of my

colleague and friend, George Cole.

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Introduction

In choosing a title, we had in mind that there are many planetary systems other than the Solar System. This book is concerned with the science associated with the planets, the stars that they orbit and the interactions between them. The relationships of several extrasolar planets to their parent stars differ from that of any solar-system planet to the Sun, and this can give clues either about the way that planets are formed or the way that they evolve after formation. For this reason, we conclude with a chapter that gives current ideas about the way that planetary systems have come into being. There is general agreement that the formation of planets is intimately connected with the formation of stars – although there are important differences of view about the nature of the connection. To give a rounded and complete picture, we include material on the formation, evolution and death of stars and those properties of the Sun that influence the planets of the Solar System.

The origin of the study of the Solar System, at a truly scientific level, occurred in the seventeenth century when Isaac Newton explained the motion of solar-system bodies by the application of the laws of mechanics combined with the inverse-square law of gravitational attraction. With subsequent improvements in telescope technology and, latterly, through the achievements of space science, we now have detailed descriptions of many solar-system bodies and have been able to analyse samples from some of them. The range of what constitutes stellar and planetary science has expanded in almost explosive fashion in the last few decades and includes aspects of many different conventional sciences – although physics and astronomy certainly predominate. In the Introduction to the First Edition, the important feature of planetary science – that it develops so quickly – was stressed. The decade since the first edition was published has illustrated this rapid development in many ways. There have been a large number of new observations, new theories and new interpretations of what has been known for some time. As an example of this, Pluto, once regarded as the 'ninth planet', is now designated as a *dwarf planet* for reasons that are explained in Chapter 9. Other changes from the First Edition have been implemented because second thoughts have suggested alternative treatments of material, the addition of new material and, sometimes, the exclusion of original material.

There are many excellent textbooks that describe stars and the Solar System in some detail and give qualitative explanations for some features and quantitative explanations where the underlying science is not too complicated. At the other extreme, there are monographs and papers in learned journals that deal with aspects of stellar and planetary science in a rigorous and formal way that is suitable for the specialist and where, sometimes, jargon is used that is incomprehensible to the layman. The readership we have in mind for the present work is the senior undergraduate student in physics or astronomy or the new graduate student working in planetary science who requires an overview of the subject before embarking on a detailed study of one specific aspect. Our analyses of stellar and planetary science are aimed to be accessible to such students – or, indeed, to any others meeting the field for the first time.

There are two main components of this text. The first of these is a general overview of the nature of stars and of the Solar System that can be read independently and quotes the important results that have been obtained by scientific analysis. For those unfamiliar with stellar properties or the overall structure of the Solar System, we recommend that this part should be read before looking at the other material to acquire a general picture of the system as a whole and the interrelationships of the bodies within it.

The second component is that which justifies the title of this work. It is a set of 43 appendices in which the detailed science is described. The appendices are very variable in length. Some, for example, Appendix B that deals with mineralogy, are as long as a normal chapter of a book. Others, for example, Appendix AH that is concerned with the mechanical interactions of radiation and matter, are quite brief. Together, these topics provide a description of the bulk of the underlying science required to explain the main features of the Solar System.

Problems are given at the end of chapters and most appendices, designed to give the reader a quantitative feeling for stellar and solar-system phenomena. Some of these problems are of a trial-and-error nature in which various possible solutions are tested to find the one that gives the correct solution. While these can be done with a hand calculator, they can be done more quickly by writing a simple computer program, usually consisting of no more than half a dozen lines of code. Two larger-scale computer programs are provided, which are listed in the appendices. This additional material is also available from the CRC Web site: http://www.crcpress.com/product/isbn/9781466563155.

Our Earth and the other planets have undergone substantial changes in their states over many aeons by the action of natural forces. An understanding of the nature of the Solar System and of the influences that govern its behaviour may allow an appreciation to be developed of what can influence our planet in the future.

Sadly, at about the time the idea of a second edition was raised, my coauthor George Cole died after a short illness. I undertook the preparation of the Second Edition on my own, and although there are many changes, much of George Cole's contribution is still present, and his imprint remains strong in the Second Edition.

Michael M. Woolfson

1

Unity of the Universe

Studies of the Universe show that it is a coherent entity and not a number of disconnected and unrelated objects. Viewing dense gas clouds, stars and galaxies, either nearby or in deepest space (which is equivalent to observing the Universe either in very recent times or long ago), shows the same formations involving broadly the same chemical compositions. For this reason, it is possible to consider a representative galaxy, a representative type of star, or a representative dense cloud of material in considering the nature of these objects. There are, of course, large variations of size and mass, but for compositions, the variations are relatively small deviations about some mean.

1.1 Cosmic Abundance of the Chemical Elements

The composition of distant astronomical objects can only be determined by analysing the electromagnetic radiation that they either emit or absorb. This radiation can cover the full range of the electromagnetic spectrum from the high-energy end, gamma (γ) rays, to the low-energy end, radio waves. The underlying theory of this kind of observation is described in Appendix A. The information derived from these observations can be about the atomic composition of the body; about the state of ionisation of the atoms present, which is an indication of the prevailing temperature; or about the presence of molecular species, for example, water, methane or carbon dioxide.

This procedure has its limitations. The interiors of bodies cannot be examined if the radiation cannot escape so that, for example, the composition of only the surface regions the Sun can be found. To infer the composition of the inner regions requires the exercise of theory, which may need to be modified from time to time in the light of increasing information. Taking this uncertainty into account, the relative cosmic abundance of the chemical elements is generally accepted as that given in Table 1.1.

Hydrogen and helium, which is an inert gas, are overwhelmingly the most abundant elements. The second most abundant chemically active element is oxygen, and since the oxide of hydrogen is water, H_2O, this molecule, in its various phases, is abundant in the Universe. The fourth and fifth most abundant elements, carbon and nitrogen, are also chemically active giving simple compounds such as carbon monoxide, CO; carbon dioxide, CO_2; ammonia, NH_3; and methane, CH_4. The basis of life on Earth are the structures of deoxyribonucleic acid, DNA, the blueprint material of life; ribonucleic acid, RNA, the chemical computer program that controls the formation of proteins; and the proteins themselves, which provide the substance and working materials of living matter (Section AN.3). These are all carbon-based organic compounds, consisting mostly of carbon, nitrogen, oxygen and hydrogen, with some sulphur and phosphorus and, in the case of proteins, other elements, especially some metals.

Silicon is a relatively abundant element, as are magnesium, aluminium, calcium, sodium, potassium and iron. These elements, together with oxygen, form the great bulk of the silicate

TABLE 1.1

Relative Cosmic Abundance of the Chemical Elements

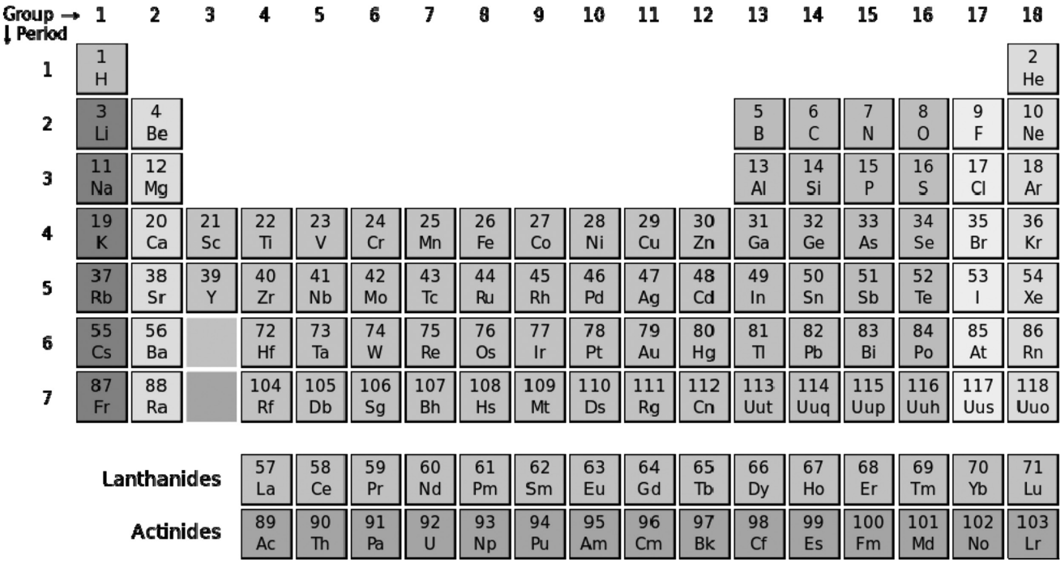
Element	Relative Number of Atoms	Relative Masses
Hydrogen, H	7.5×10^8	7.5×10^8
Helium, He	5.8×10^6	2.3×10^8
Oxygen, O	6.3×10^5	1.0×10^7
Carbon, C	4.2×10^5	5.0×10^6
Nitrogen, N	7.1×10^4	1.0×10^6
Neon, Ne	6.5×10^4	1.3×10^6
Silicon, Si	2.5×10^4	7.0×10^5
Magnesium, Mg	2.5×10^4	6.0×10^5
Iron, Fe	2.0×10^4	1.1×10^6
Sulphur, S	1.6×10^4	5.1×10^5
Argon, Ar	5.0×10^3	2.0×10^5
Aluminium, Al	1.9×10^3	5.1×10^4
Calcium, Ca	1.8×10^3	7.2×10^4
Nickel, Ni	1.0×10^3	5.9×10^4
Sodium, Na	8.7×10^2	2.0×10^4

materials that constitute a large proportion of the Earth. Other non-silicate minerals, such as oxides and sulphides, also occur, but they are much less common. Iron, plus some nickel and possibly sulphur in the form of the mineral troilite (iron sulphide, FeS) constitutes the Earth's core. Minerals form according to the local conditions of pressure and temperature and whether, in particular, cooling processes take place quickly or slowly. A systematic description of different kinds of minerals and the rocks they form is given in Appendix B.

For condensed matter, there are a few rules that control the nature of the material formed, governed by the affinities of different atoms to form different types of bonds. In many cases, the elements segregate into silicate, sulphide and metal according to the following general rules, governed by the positions of elements in the periodic table (Figure 1.1):

- Elements in groups 1 and 2 of the periodic table have a tendency to combine with oxygen in oxides and silicates. Elements such as potassium, K; barium, Ba; sodium, Na; strontium, Sr; calcium, Ca; magnesium, Mg; and rubidium, Rb are called *lithophilic* elements (from the Greek for stone, *lithos*) because they tend to be found in stony materials.
- Elements in groups 11–16 of the periodic table that are either metallic or *metalloid,* that is, materials with properties of both metals and non-metals, tend to appear as sulphides. Thus, copper, Cu; zinc, Zn; lead, Pb; tin, Sn; and silver, Ag are called *chalcophilic* elements (after the Greek *khalkos* for their leading member, copper).
- Some elements may have only weak affinities for oxygen and sulphur so that, while they do form compounds, for example, silicates or sulphides, they may also appear in metallic form. Such elements are iron, Fe; nickel, Ni; cobalt, Co; iridium, Ir; platinum, Pt; and gold, Au. These are called *siderophilic* (after the Greek *sideros* for iron, their representative element).

A detailed analysis of the chemical affinities in different conditions is quite complicated, but these simple rules often apply and are useful in understanding particular situations.



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

FIGURE 1.1
(See colour insert.) Periodic table. Elements in the same column have similarities in chemical behaviour.

1.2 Some Examples

To illustrate the degree of uniformity of chemical compositions in different locations, we now compare the mean compositions of the Solar System, the Orion Nebula and a planetary nebula – which has nothing to do with planets but is ionised material thrown out by an evolving star in its red-giant stage of development (Section J.4). Data for 13 chemical elements are listed in Table 1.2. The similarities between the three lists are quite striking, taking into account the diverse nature of the sources.

TABLE 1.2
Log_{10} (Relative Abundance), Normalised to Hydrogen as 12, for Three Different Entities

Element	Solar System	Orion Nebula	Planetary Nebula
H	12.00	12.0	12.00
He	10.9	11.04	11.23
C	8.6	8.37	8.7
N	8.0	7.63	8.1
O	8.8	8.79	8.9
F	4.6		4.9
Ne	7.6	7.86	7.9
Na	6.3		6.6
S	7.2	7.47	7.9
Cl	5.5	4.94	6.9
Ar	6.0	5.95	7.0
K	5.5		5.7
Ca	6.4		6.4

TABLE 1.3

Relative Abundance by Percentage Mass for Regions of the Earth and Venus

Oxide	Earth (Continental Crust) (%)	Earth (Oceanic Crust) (%)	Venera 13 Site (%)	Venera 14 Site (%)
SiO_2	60.1	49.9	45	49
Al_2O_3	15.6	17.3	16	18
MgO	3.6	7.3	10	8
FeO	3.9	6.9	9	9
CaO	5.2	11.9	7	10
TiO_2	1.1	1.5	1.5	1.2
K_2O	3.2	0.2	4	0.2

Note: The hostile conditions on Venus made rapid measurements essential; pressure, temperature and chemical attack destroyed each probe after about 20 min.

As would be expected, similar bodies frequently display similar mineral compositions. This is shown in Table 1.3 for a selection of minerals on the Earth and Venus, often regarded as sister planets because of their similar size and mass. The table gives components of minerals, as described in Section B.3, rather than complete minerals. It will be seen that there are different compositions for different kinds of site on Earth and for the sites of the landers of the Venera space programme of the Soviet Union. The Venus data most resemble that of oceanic-crust material on Earth.

Meteorites are a rich source of information about the minerals present in the Solar System. The age of the vast majority of meteorites, as measured by radioactive dating (Appendix C), is about 4.5×10^9 years, which is the accepted age for the Solar System as a whole. A list of the most common minerals found in meteorites is given in Table 1.4; they are similar to those on Earth. Meteorites are mostly fragments of asteroids (Chapter 8), produced when these bodies occasionally collide.

These examples, involving minerals, exclude hydrogen, H, and helium, He, the most abundant elements, but these are the major components of larger bodies. It is known that all normal stars are made mostly of hydrogen with a substantial component of helium and a small admixture of other elements. This also applies to the major planets of the

TABLE 1.4

Minerals Most Commonly Found in Meteorites

Mineral	Composition
Kamacite	(Fe, Ni) (<7% Ni)
Taenite	(Fe, Ni) (>25% Ni)
Troilite	FeS
Olivine	$(Mg, Fe)_2 SiO_4$
Orthopyroxene	$(Mg, Fe) SiO_3$
Pigeonite	$(Ca, Mg, Fe) SiO_3$
Diopside	$Ca(Mg, Fe) Si_2O_6$
Plagioclase	$(Na, Ca) (Al, Si)_4 O_8$

TABLE 1.5

Main Components of the Visible Regions of the Sun and the Major Planets by Mass Percentage

Molecule	Sun (%)	Jupiter (%)	Saturn (%)	Uranus (%)	Neptune (%)
H_2	85	89.9	96.3	82.5	80.0
He	15	10.2	3.3	15.2	19.0
H_2O	0.11	4×10^{-4}	—	—	—
CH_4	0.06	0.3	0.3	2.3	1.5
NH_3	0.016	0.026	0.012	—	—
H_2S	0.003	—	—	—	—

Solar System. A comparison between the main surface components of the Sun and the major planets is shown in Table 1.5.

There is a general similarity between the different bodies in the table, but it must be stressed that these are surface components and do not refer directly to the interiors. There is, nevertheless, for Saturn and Jupiter the implicit assumption that these percentages would be very broadly the same as for the Sun if the full planetary inventory could be taken. The basis of this assumption is that these large and massive planets would have been formed from similar material that formed the Sun and that the escape velocity from them is so large that they would have retained the complete original inventory. On this basis, the interior of Saturn, and to a lesser extent of Jupiter, should contain a greater helium concentration than in surface regions. On the other hand, the lesser proportion of hydrogen detected in Uranus and Neptune may be due to losses from these lower mass planets for which escape velocities are also lower, although there is another possible explanation (Section 12.15).

Wherever we look in the cosmos, we see very similar grouping of the chemical elements. It would seem safe to assume that the material composition of the Solar System and its neighbourhood is not untypical of such systems everywhere.

Problems

1.1 It is estimated that the following are the percentages by mass of various elements in the composition of the Earth:

Iron	31.7
Silicon	15.1
Magnesium	13.9
Calcium	1.5
Aluminium	1.4

Calculate the mass ratios for X:Fe; for X = Si, Mg, Ca and Al for the Earth; and for the cosmic abundances given in Table 1.1. What deduction do you draw from these results?

1.2 Seventy percent of the Earth's surface is covered by water with an average depth of 3.8 km. Continental crust has an average thickness of 40 km and density 2700 kg m^{-3}. Oceanic crust has an average thickness of 7.5 km and density 3300 kg m^{-3}. Assuming that Table 1.3 gives the total oxygen content of the crusts and that oceans and seas are pure water with density 1000 kg m^{-3}, find the ratio of the amount of oxygen contained in the combined crusts to that contained in the oceans and seas.

You will need the following information:

Element	Atomic Weight	Element	Atomic Weight
Oxygen	16	Potassium	39
Magnesium	24	Calcium	40
Aluminium	27	Titanium	48
Silicon	28	Iron	56

1.3 The density distribution of Saturn is modelled as

$$\rho = \rho_0\left\{1-\left(\frac{r}{R}\right)^{1/4}\right\}$$

where

ρ_0 is the central density
r is the distance from the centre
R is the radius of the planet

The proportion of helium by mass is assumed to vary as

$$p = p_0(1-\alpha r)$$

where

p_0 is the central proportion
α is a constant

It is known that the surface proportion of helium is 0.033 and that the average for Saturn as a whole is 0.15.

1. What is the mass of Saturn in terms of ρ_0 and R?
2. What is the mass of helium in terms of ρ_0, p_0 and R?
3. What is p_0?

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